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ScienceDirect
Vision Research 47 (2007) 2115–2123
Vision Research
www.elsevier.com/locate/visres

What is the minimum field of view required for efficient navigation? ☆

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Received 31 August 2006; received in revised form 22 February 2007

Abstract

Critical points were computed to determine the minimum field of view (FOV) size required for efficient navigation. Navigation performance in 20 normally sighted subjects was assessed using an immersive virtual environment. Subjects were instructed to walk through a virtual forest to a target tree as quickly as possible without hitting any obstacles (trees, boulders, and holes). The navigation task was performed in three FOV and image contrast conditions under binocular, monocular, chromatic and achromatic viewing conditions. FOV was constricted to 10°, 20° and 40° diameter and average image contrast was nominally high (11%), medium (6%) and low (3%). Navigation performance was scored as latency in walk initiation, walk time to reach goal and the number of obstacle contacts. The results revealed a linear relationship between log FOV and the two time measures, log latency and log walk time. The slopes of the linear regressions for log latency and log walk time ranged between –0.11 and –0.41. Critical points were computed from the non-linear relationships found between the number of obstacle contacts and FOV. The critical points for efficient navigation were FOVs of 32.1°, 18.4° and 10.9° (diam.) for low, medium and high image contrast levels, respectively, highlighting the importance of contrast on the size of the FOV required for efficient navigation. Neither binocularity nor image chromaticity significantly affected navigation performance. The findings of this study have important implications in the design and prescription of head mounted displays intended to augment navigation performance.

Keywords: Efficient navigation; Field of view; Image contrast; Critical points; Walking

1. Introduction

The visual system is essential to achieving safe and efficient travel as evidenced by the reduction in mobility performance in people who are visually impaired (Brown, Brabyn, & Welch, 1986; Geruschat, Turano, & Stahl, 1998; Kuyk, Elliott, & Biehl, 1996; Lovie-Kitchin, Mainstone, & Robinson, 1990; Marron, 1982 #11). With vision, a traveler can acquire information about the surrounding environment from which the intended travel path can be planned and obstacles detected and subsequently avoided.

Studies investigating the visual function(s) that best predict navigation performance have consistently shown that measures of visual field (VF) and/or contrast sensitivity (CS) emerge as the best predictors of navigation performance, accounting between 39% and 70% of the variance in navigation performance (Black, Lovie-Kitchin, & Woods, 1997; Geruschat et al., 1998; Haymes, Guest, & Heyes, 1996; Kuyk & Elliott, 1999; Long, Rieser, & Hill, 1990; Marron & Bailey, 1982). Despite the demonstrated importance of the VF to navigation, questions still remain regarding how small the field of view (FOV) could be and still achieve safe and efficient navigation.

Pelli (1987) was the first researcher who attempted to address in a systematic manner the issue of how small a VF could be and not affect navigation. He artificially restricted the VF of persons with normal vision as they traveled in order to determine a *critical point* for

☆ This study has not been published elsewhere and is not under review with any other journal.

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doi:10.1016/j.visres.2007.03.012

navigation, i.e. the "severest restriction at which performance is only slightly impaired". He measured travel time and number of bumps on an obstacle course and shopping mall and found the *critical points* to be 5° and 2° (radius) for the two environments, respectively. He also artificially reduced the contrast of the subjects and found *critical point* estimates of 4% and 2% of normal contrast for the same environments.

The *critical-point* estimates determined by Pelli (1987) are low compared to the size of the VFs and CS of people with visual impairment who report and exhibit orientation and mobility problems. Pelli acknowledged the discrepancy and suggested that the difference might be due to how persons with vision impairment calculate and respond to the risk involved in independent travel. However, another possibility is that the two vision factors, VFs and contrast, interact in determining the *critical point* for navigation. Persons with vision impairment often have reductions in both VFs and CS. Because Pelli tested the two factors separately, the manner in which a reduction in one factor affects the *critical point* of the other is unknown.

It is likely that contrast affects the VF *critical point*. Several studies have shown that CS is greatest at the fovea after which it declines monotonically with eccentricity (Pointer & Hess, 1989; Regan & Beverley, 1983; Rijsdijk, Kroon, & van der Wildt, 1980; Robson & Graham, 1981; Wright & Johnston, 1983). Because of this relationship, a reduction in the contrast level (of the target or overall environment) would effectively constrict the functional VF in the absence of any physical VF loss. Therefore, decreasing the functional FOV through a decrease in the contrast level could, in turn, result in an increase in the VF *critical point*. The primary aim of this study was to estimate the VF *critical point* for efficient navigation and to determine its dependency on contrast.

Another area of mobility research that has received little attention includes the effects of different viewing conditions on navigation performance. Specifically, are the effects of FOV and image contrast on navigation performance altered whether or not the person is navigating with one or two eyes, or whether they navigate within a color or achromatic environment? Knowing how different viewing conditions affect the relationship between navigation performance under different FOV and image contrast levels not only increases the generalizability of the results but it also has important implications in the design and choice of field-restricting mobility devices, such as head-mounted displays (HMDs). As such, a secondary aim of this study was to determine whether or not the presence or absence of binocular viewing or color interact with the manner in which either FOV or image contrast affect navigation performance.

In this study, we measured navigation performance (latency, walking time and number of obstacle contacts) under conditions of reduced FOV and contrast, in monocular and binocular viewing conditions, with chromatic and achromatic scenes.

2. Methods

2.1. Subjects

Twenty normally sighted adult subjects participated in the study. Their ages ranged from 22 to 38 years, with a mean of 30.0 ($SD = 4.6$) years. Inclusion criteria were habitual visual acuity (VA) of at least 0.00 logMAR (20/20), habitual contrast sensitivity (CS) of at least 1.75 logCS and full visual fields (VF) in each eye. The Lighthouse ETDRS acuity chart (Ferris, Kassoff, & Bresnick, 1982) was used to measure habitual VA. The chart was transilluminated at approximately 100 cd m^{-2} and acuity was measured letter-by-letter and reported as the logarithm of the minimum angle of resolution (logMAR) (Bailey & Lovie, 1976). Habitual CS was measured using the Pelli–Robson letter contrast sensitivity chart (Pelli, Robson, & Wilkins, 1988) at a working distance of 1 m with overhead illumination of 85 cd m^{-2}. Habitual CS was scored as the number of letters correctly identified using the method of Elliott, Whitaker, and Bonette (1990) and Elliott, Bullimore, and Bailey (1991). The VF of subjects was measured using kinetic perimetry with a Goldmann perimeter (III4e target on a background luminance of 10 cd m^{-2}) along 24 meridians from radii of 70° vertically and 90° horizontally.

Exclusion criteria, identified either from questioning or from observations while participating in the study, included the presence or history of a physical or cognitive disorder that affected their ability to walk or follow instructions. All subjects were unfamiliar with the experimental design.

Informed consent was obtained from each subject after the nature and possible consequences of the study were described as was approval from the Johns Hopkins Medical Institutions' committee on human experimentation. The research followed the tenets of the Declaration of Helsinki.

2.2. The virtual environment

To ensure precise control over the environment and particularly the image properties in this study, we measured navigation performance in a virtual environment. In this way, we could be assured that each subject was tested under identical viewing conditions, with the same objects in the same locations under the same lighting conditions, with no uncontrolled visual factors. Using a head mounted display (HMD), we artificially restricted the field of view (FOV) of persons with normal vision and had them walk to a target in a virtual forest under various contrast levels.

An immersive virtual reality system was used to display a forest scene. The virtual forest, which was modeled in 3D Studio Max (Discreet, Montreal, Canada), was exported to a graphics engine developed in-house with C++ and Microsoft's DirectX. Using the output from a HiBall head tracker (3rd Tech, Chapel Hill, NC), which was attached to the top of the HMD, along with the imported forest scene, the graphics engine determined the subject's current point of view in the environment. A GeForce FX graphics board (nVIDIA, Santa Clara, CA) was then used to generate perspective views of the environment, which were displayed in the HMD.

The virtual forest consisted of a target tree, two obstacles (either a tree, boulder, or a hole in the ground), which were positioned between the starting position and the target tree, and an array of 40 distractors (30 trees and 10 boulders) (Figs. 1a and b). The target tree was distinguishable from the other trees by its swirling bark pattern on its trunk (shown in Fig. 1a). The target tree was located on a horizontal plane 9 m from the starting point in one of five positions (0, ±0.33, or ±0.67 m offset from the starting point). The two obstacles, one at 3 m and the other at 6 m, were offset laterally from the starting point by ±0.33 m, in the opposite direction to each other.

To illustrate how the placement of the two obstacles created the need for obstacle avoidance, Figs. 2a and b show top-down views of representative paths taken by two different subjects. One subject successfully avoided the obstacles lying in the direct path between the starting point and the target tree (Fig. 2a), while the other subject did not (Fig. 2b).

With the exception of two distractor trees that were placed at fixed positions to prevent subjects from walking into the walls of the physical room and the two obstacles described above, all other distractors were

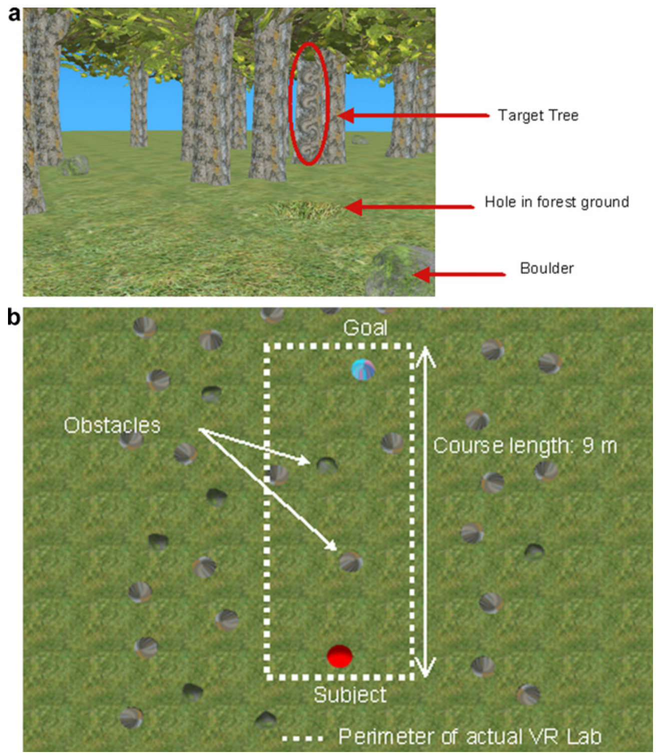

Fig. 1. (a) Sample scene of the virtual forest illustrating the appearance of the target tree and obstacles. (b) Aerial perspective of the virtual forest illustrating the spatial layout of the starting point, target tree and obstacles relative to the actual size of the test laboratory.

located beyond the actual perimeter of the laboratory (Fig. 1b). As a result, subjects saw an expansive forest, but were unable to navigate through the majority of it. At no time, could subjects see themselves within the scene of the HMD.

Subjects were accompanied on every trial by an experimenter who put up her arm whenever subjects walked close (~0.5 m) to one of the laboratory walls. If a subject walked into the experimenter's arm, they were informed to change their direction but were never advised in what direction to modify their course. Subjects veered within 0.5 m of the laboratory walls on average in 8.6% of trials. An audible sound was generated whenever a subject contacted an obstacle.

A total of 45 forest configurations were created in order to test five trials for each of the three FOV and three image contrast conditions. FOV was restricted to 40°, 20°, or 10° in diameter using a circular mask that was centered relative to the center of each display. Areas outside of the circular mask were blacked out. Image contrast levels were nominally high, medium (50% contrast of the highest level) or low (25% contrast of the highest level). Because image contrast is dependent upon the currently displayed view, it is not feasible to calculate the actual image contrast values. However, we were able to measure average image contrast, $C(x,y)$, on a subset of the views under the three contrast levels using the equation:

$$C(x,y) = \mathrm{abs}(L(x,y) - L_0)/L_0$$

where $L(x, y)$ = the luminance at point x, y contained within a given FOV

L_0 = the mean luminance value of all the pixels in the image within the same FOV.

The means of the average image contrast levels were 11%, 6% and 3% for high, medium and low contrast levels, respectively.

Experimental trials were divided into 3 blocks of 15 trials where the FOV size was held constant within a given block, but the presentation order of the three image contrast levels and the position of the target tree and obstacles were randomized within each block. The order in which blocks were tested was counterbalanced across subjects.

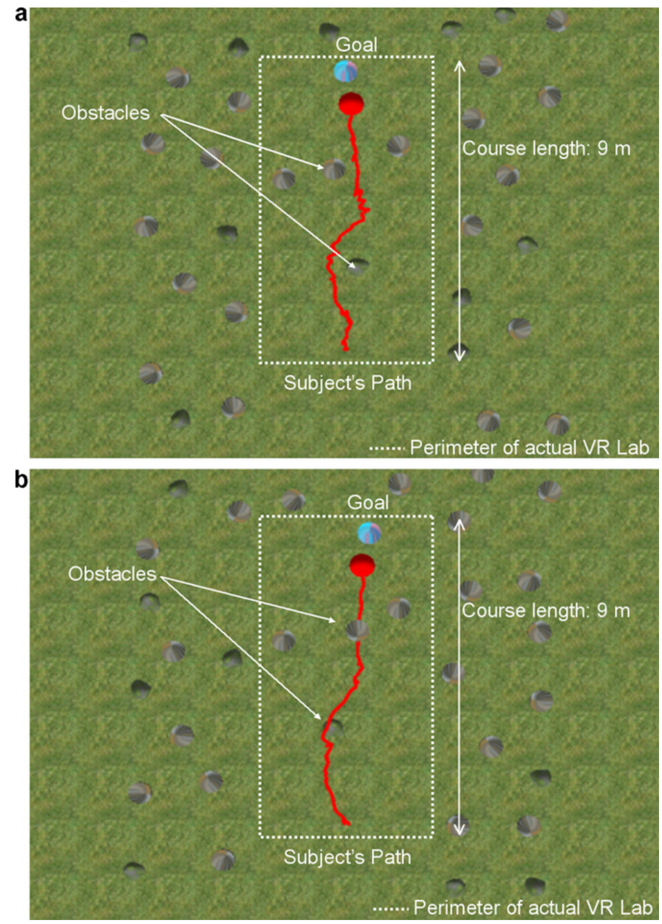

Fig. 2. (a) Top-down view of a path taken by a subject who successfully avoided all obstacles lying in the path between the starting point and the target tree. (b) Top-down view of a path taken by a subject who did not successfully navigate around the obstacles lying on the path between the starting point and the target tree.

Subjects were randomly assigned to one of four different testing groups, with five subjects in each group. Group 1 performed the experiment under binocular, monochromatic viewing conditions, group 2 performed the experiment under monocular, monochromatic viewing conditions, group 3 performed the experiment under binocular, chromatic viewing conditions and group 4 performed the experiment under monocular, chromatic viewing conditions.

2.3. Apparatus

2.3.1. Head and eye tracking

Head position and orientation were monitored using a HiBall-3000 Optical Tracker (3rd Tech, Chapel Hill, NC) and sampled every 7 ms. Tracker precision is reported to be 0.2 mm, with an angular precision less than 0.03° (Welch, Bishop, & Vicci, 2001). The output of the head tracker was filtered using an exponentially weighted smoothing function and point of view was calculated from the head position and orientation data. The lag between the head movement and display update was 116.7 ms. To filter out oscillations associated with gait and to determine walking path, Daubechies wavelet transform of the sixth order was applied to the head-tracker data (see Ismail & Asfour, 1999).

2.3.2. Head-mounted display

The display device was a HMD system (a modified Low Vision Enhancement System developed by Robert Massof at the Wilmer Eye Institute). The headset contained two color microdisplays (SVGA,

800×600 3D OLED Microdisplay, Emagin Corp.). The FOV of each was 53° (H) × 41° (V), with spatial resolution of approximately 0.06°/pixel. The displays have a refresh rate of 60 Hz. For the binocular viewing condition, spatially offset images were sent to each display to produce stereoscopic viewing.

2.4. Procedure

Prior to starting the experiment, subjects were shown, with the largest FOV setting in the HMD (i.e. 53° × 41°), a scene of the virtual forest. This was done so that subjects could become accustomed with the obstacles, the target tree and the experimental task. The subjects were instructed to walk through the obstacles to familiarize themselves with the audible sound that they would hear if ever they contacted an obstacle during the actual trials. Subjects also had to demonstrate to the experimenter that they were able to distinguish the target from the distractor trees by walking up to an example of each object type. Following this introductory phase, subjects were given five practice trials with randomly selected FOV sizes and image contrast levels and they were asked to perform the experimental task of walking to the target tree without hitting any of the obstacles. Participants were instructed to use the time during the practice trials to become familiar with moving in the virtual world.

Following the completion of the practice trials, the experiment was started. Subjects were instructed to walk to the target tree as quickly as possible without hitting any obstacles. Participants were also informed that they could take a break at any time when needed.

2.5. Analyses

Navigation performance in this study was characterized as three different outcome variables: latency, walk time and the number of obstacle contacts. Latency was defined as the time (in seconds) from display onset until the subject's first step. Walk time (in seconds) was the time from the subject's first step until s/he reached the goal (target tree). The number of obstacle contacts within a trial was recorded as the number of times the distance between the center of an obstacle and the center of the subject's body was less then 0.625 m. Performance scores for latency, walk time and obstacle contacts were computed for all subjects under all nine test conditions (3 FOV × 3 image contrast levels).

The *critical point* for navigation represents the minimum FOV that is required for efficient navigation. Decreases in the FOV from the *critical point* correspond to decrements in navigation performance. Pelli (1987) did not report specific details about the method he used for computing *critical points*. Therefore we adopted the methods described by others to derive *critical points* for various activities (Bertera & Rayner, 2000; Bullimore & Bailey, 1995; Crossland & Rubin, 2006; Rayner, 1975).

C*ritical points* for efficient navigation, calculated for each contrast level, were defined as the value of the outcome measure that corresponded to a 25% performance decrement from baseline. Baseline was defined as performance at the largest tested FOV, which was 40°, for each contrast. A cut-off value of 25% was selected for comparability to the traditional 75% threshold level.

Prior to estimating the *critical points*, a smoothing spline was fit to each outcome measure as a function of FOV in order to examine the shape of the function. Within the traditional definition, *critical points* are unspecified for an outcome measure that is related in a linear manner over the entire tested range. For the outcome measures that were non-linearly related to FOV, an exponential model was fit to each outcome measure as a function of FOV, using a least squares approach, and these functions were used as the basis for the *critical-points* calculations.

To assess for the effects of binocularity, chromaticity, FOV and image contrast on the three outcome measures of navigation performance, regression models were used. The generalized estimated equation (GEE) approach was utilized to correct the standard errors to account for correlations within measures of the same subject. For each navigation performance measure, FOV and image contrast levels were entered into the GEE model as indicator variables and significant effects were assessed. Interaction terms between FOV and image contrast as well as binocularity and chromaticity were also included in the GEE model to assess whether or not significant differences in navigation performance existed under the different FOV sizes and image contrast levels and whether or not these trends changed with binocularity or chromaticity.

All statistical analyses were conducted using JMP for Windows (JMP© 5.1) and Statistical Analysis Systems (SAS© 8.2). Data distributions were assessed for normality using the one sample Kolmogorov–Smirnov test. Those data distributions that were significantly different from a normal distribution were transformed using a logarithm ($\log_{10}$) transformation. With the exception of the obstacle contacts data, the log transformations in the majority of cases lead to normality of data distributions. As a result, normal models were specified for the distributions of log latency and log walk time in their respective GEE models. To accommodate for non-normality and over-dispersion in the obstacle contacts data, a negative binomial model was specified for the GEE models for obstacle contacts.

3. Results

Figs. 3a and b show the functions of latency and walk time with FOV, respectively. As shown, log latency and log walk time are linearly related to log FOV over the range that we tested. Therefore, as the FOV decreased, navigation performance also decreased.

Fig. 3c shows the relationship between the number of obstacle contacts as a function of FOV for the three contrast levels. The lines are the best-fit exponential functions to the data. The subjects under high and medium image contrast levels made on average 0.2–0.3 obstacle contacts with a FOV as small as 20° diameter. However, the average number of obstacle contacts doubled with a 10° FOV. Under low image contrast, the number of obstacle contacts always increased with each reduction in FOV size. The average number of obstacle contacts was 0.3 under the 40° FOV size at low image contrast level, but this number doubled and then tripled under the 20° and 10° FOV sizes, respectively.

Because both log latency and log walk time varied in a linear manner with log FOV, *critical points* based on those two outcome measures were unspecified. The number of obstacle contacts varied in a non-linear manner with FOV. Therefore, we computed VF *critical points* for efficient navigation based on the number of obstacle contacts. The results revealed different *critical points* for the three contrast levels, 32.1°, 18.4° and 10.9° diameter for the low, medium and high image contrast levels, respectively.

The results from the multiple regression analyses (point estimates, confidence intervals, standard errors and significance levels) are listed in Tables 1 and 2. Table 1 reports only the main effects of FOV and image contrast on the navigation outcome measures of log latency and log walk time, since no significant interactions were found between FOV and image contrast for log latency and log walk time ($p > 0.05$). Significant interactions were found however between FOV and image contrast for obstacle contacts and these results are detailed in Table 2.

As noted in Table 1, log latency and log walk time were adversely affected by reductions in FOV and image con-

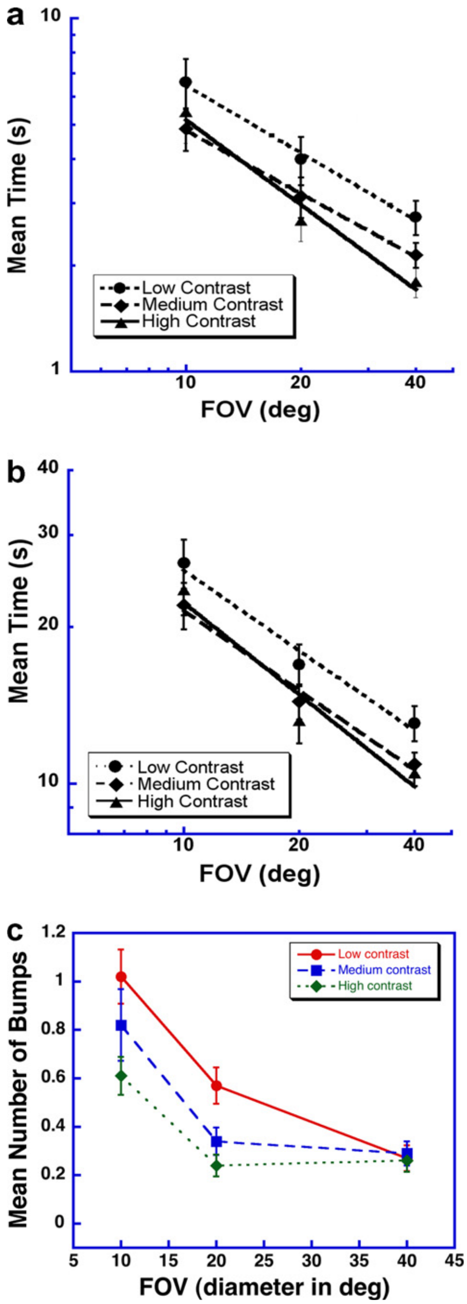

Fig. 3. (a) Graph illustrating the inverse linear relationship between log mean time and log FOV for the navigation performance measure of latency. (b) Graph illustrating the inverse linear relationship between log mean time and log FOV for the navigation performance measure of walk time. (c) Graph illustrating the non-linear relationship between the average number of obstacle contacts and FOV.

trast. For the FOV manipulation, navigation performance with the 40° FOV was significantly better than performance with either the 20° and 10° FOV and performance with the 20° FOV was significantly better than performance with the 10° FOV.

Image contrast also significantly affected navigation performance. Log latency and log walk time were significantly higher (decreased performance) under low contrast conditions compared to the medium and high contrast conditions. No significant difference in navigation performance was found for log walk time between the high and medium image contrast levels. There was however a significant increase in mean time between high and medium image contrast conditions for log latency.

A significant interaction was found between FOV and image contrast for the number of obstacle contacts. Thus the effects of a reduced FOV on the number of obstacles contacted varied as a function of image contrast. Under low image contrast, significantly more obstacles were contacted with either the 10° and 20° FOV compared to the 40° FOV and significantly more obstacles were contacted with the 10° FOV than with the 20° FOV (Table 2). Under medium and high image contrast levels, the number of obstacle contacts was significantly greater with the 10° FOV compared to the 20° and 40° FOV, however, no significant difference was found in the number of obstacles contacted between the 20° and 40° FOV (Table 2).

For the effect of image contrast on navigation performance scored as the number of obstacle contacts, we found that significantly more obstacles were contacted under low image contrast levels compared to high and medium image contrast levels. No significant difference in the number of obstacles contacted was found between the medium and high image contrast levels (Table 2).

The results of the manipulation of binocularity and display color are also reported in Tables 1 and 2. The effects of FOV and image contrast on all outcome measures of navigation performance were not significantly affected by the presence or absence of binocularity or display color.

4. Discussion

4.1. Critical FOV size for navigation

The primary aim of this study was to estimate the minimum FOV size that is required for efficient navigation and to determine if these estimates varied as a function of image contrast. Our findings suggest that image contrast affects the minimum FOV size required for efficient navigation. We found that the FOV required for navigation was largest under the low image contrast condition (32.1° diam.) and smallest under high image contrast (10.9° diam.). The FOV required for navigation under medium image contrast lay between the FOVs found with low and high image contrast levels (18.4° diam.). Reducing the contrast resulted in a functional constriction of the VF apart from an actual VF loss. To achieve the same level of navigation performance under low image contrast as at high image contrast levels, a larger VF is required.

The dependency of the FOV size with contrast indirectly supports the results of previous research showing that CS decreases monotonically with increasing eccentricity from the fovea (Pointer & Hess, 1989; Regan & Beverley, 1983; Rijsdijk et al., 1980; Robson & Graham, 1981; Wright & Johnston, 1983). As illustrated in the relationship between CS and eccentricity (Fig. 4), the extent of the curve bounded

Table 1
Multivariate regression model results listing the main effects of FOV and image contrast for the outcome navigation performance variables ($\log_{10}$) latency and ($\log_{10}$) walk time

Parameter[a]	Navigation performance measure[b]							
	($\log_{10}$) latency				($\log_{10}$) walk time			
	Estimate	(*SE*)	CI	*p*-Value	Estimate	(*SE*)	CI	*p*-Value
FOV								
10^0 vs 40^0	0.339	0.041	0.26 – 0.42	<.0001	0.274	0.029	0.22 – 0.33	<.0001
20^0 vs 40^0	0.139	0.034	0.07 – 0.21	<.0001	0.092	0.025	0.04 – 0.14	.0003
10^0 vs 20^0	0.200	0.041	0.12 – 0.28	<.0001	0.182	0.027	0.13 – 0.23	<.0001
Image contrast								
Low vs High	0.130	0.020	0.09 – 0.17	<.0001	0.079	0.015	0.05 – 0.11	<.0001
Medium vs high	0.056	0.018	0.02 – 0.092	.002	0.012	0.011	−0.01 – 0.03	.252
Low vs medium	0.074	0.020	0.04 – 0.11	.0002	0.067	0.010	0.05 – 0.09	<.0001
Binocularity	0.0332	0.093	−0.15 – 0.22	.721	−0.053	0.052	−0.15 – 0.05	.315
Chromaticity	0.047	0.093	−0.14 – 0.23	.6146	0.009	0.052	−0.09 – 0.11	.857

[a] FOV, field of view (diameter); image contrast low (~3% contrast), medium (~6% contrast); high(~11% contrast).
[b] SE, standard error; CI, 95% confidence interval.

Table 2
Multivariate regression model results listing the interaction effects of FOV and image contrast for the navigation outcome variable obstacle contacts

Parameter[a]	Obstacle contacts[b]											
	Low image contrast				Medium image contrast				High image contrast			
	Estimate	(*SE*)	CI	*p*-Value	Estimate	(*SE*)	CI	*p*-Value	Estimate	(*SE*)	CI	*p*-Value
FOV												
10^0 vs 40^0	1.330	0.249	0.84 – 1.82	<.001	1.013	0.247	0.53 – 1.50	<.001	0.854	0.195	0.47 – 1.24	<.001
20^0 vs 40^0	0.747	0.215	0.32 – 1.17	.0005	0.146	0.143	−0.12 – 0.43	.307	−0.077	0.206	−0.48 – 0.33	.709
10^0 vs 20^0	0.580	0.144	0.30 – 0.86	<.001	0.858	0.250	0.37 – 1.35	.0006	0.931	0.128	0.68 – 1.18	<.001
Binocularity	−0.016	0.240	−0.49 – 0.45	.948	−0.399	0.321	−1.03 – 0.23	.213	−0.041	0.286	−0.60 – 0.52	.885
Chromaticity	−0.063	0.241	−0.53 – 0.41	.792	0.100	0.322	−0.53 – 0.73	.756	0.295	0.285	−0.26 – 0.85	.300

[a] FOV, field of view (diameter); image contrast low (~3% contrast), medium (~6% contrast); high(~11% contrast).
[b] SE, standard error; CI, 95% confidence interval.

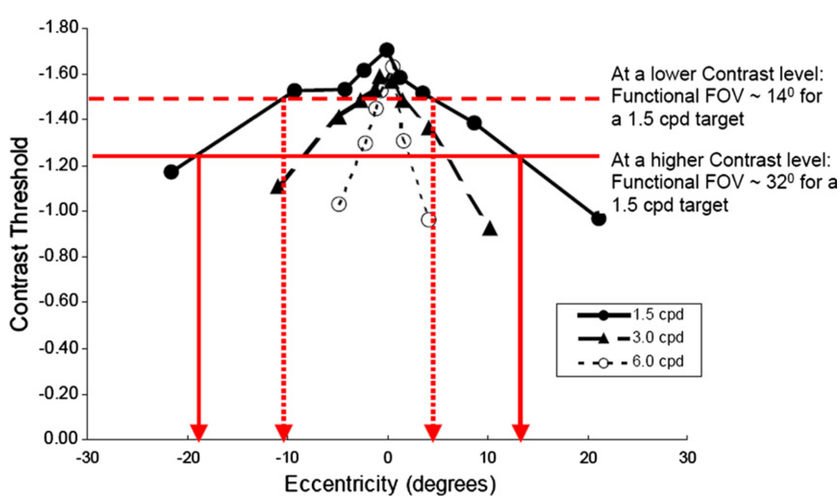

Fig. 4. Results from Robson and Graham (1981) illustrating the variation in contrast threshold for a 1.5, 3.0 and 6.0 cycle/degree grating target with eccentricity.

on either side of the fovea is not as wide for a low contrast target as it is with a target of comparatively higher contrast. Consequently, simply reducing the contrast will result in a constriction of the functional VF even before any physical VF loss. Therefore, in order to achieve the same navigation performance under low image contrast as at high image contrast levels, there has to be a corresponding increase in the VF *critical point* — a trend that is supported by our results.

The maximum spatial resolution of the HMD used in the current study was approximately 7.30 cycles/degree. Using Robson and Graham's (1981) results for the relationship between contrast and eccentricity (Fig. 4), we computed that the percentage increase in the FOV size when the contrast was reduced from a level equivalent to the current study's medium contrast level to low image contrast was 51%, 64% and 56% for grating targets of 1.5, 3 and 6 cycles/degree, respectively. These percent increases are lower than the percent increase in the VF *critical point* found in the current study (74%) for the same reduction in image contrast. No percent increase in FOV size was computed from high contrast levels, since subjects in Robson and Graham's (1981) study were unable to detect the 1.5, 3 and 6 cycles/degree grating targets at the current study's high image contrast level of 11%.

A possible reason for the small discrepancy between the percent increase in the FOV size derived from Robson and Graham's (1981) results and the current study, may relate to the determination of image contrast in the current study. As previously detailed in the methods, image contrast levels in our study were averaged over an array of contrast levels that were present within a representative scene/image in the HMD. Thus the displayed scenes/images in the HMD had contrast levels that were both greater and less than the averaged image contrast level. Consequently, our reported (averaged) image contrast levels are most likely an underestimation of the actual image contrast level and hence lower than the equivalent contrast levels from Robson and Graham's (1981) study. As illustrated in Fig. 4, a relative reduction in image contrast between our study and Robson and Graham's (1981) study, would result in a comparative decrease in our FOV size which in turn would increase our percent change in the VF *critical point* compared to the percent increase seen in Robson and Graham's (1981) study.

The VF *critical point* found under high image contrast in the present study (10.9° diam.) is however in agreement with Pelli's (1987) VF *critical point* of 10° diam. for an obstacle course, but not with his estimate of 4° for navigation through a shopping mall. It is possible that the difference in *critical point* estimates between the obstacle course and shopping mall may again be related to the average contrast level, with a higher contrast level in the mall.

Haymes et al. (1996) and Lovie-Kitchin et al. (1990) also determined what FOV size is required for navigation. Both studies made their assessments on people with actual vision loss; thus their subjects had eye-based vision loss compared to the head-based loss in the current study. Haymes et al. (1996) reported that mobility performance in subjects with peripheral VF loss resulting from Retinitis Pigmentosa (RP) was maintained until there was constriction of the VF to within the central 20° diameter VF. The average Pelli–Robson CS of their RP subjects was 1.13 log CS which equates to approximately 7.4% contrast and best matches the medium image contrast level in the current study (approximately 6%). Despite possible differences in navigation performance that may have been introduced from head-based versus eye-based vision loss, our estimate of the FOV size required for navigation under medium image contrast (18.4° diam.) is in good agreement with Haymes et al.'s (1996) estimate (20° diam.).

Lovie-Kitchin et al. (1990) reported that mobility in visually impaired subjects did not become impaired until loss of the VF encroached the central 74° diameter VF. Even though Lovie-Kitchin et al. (1990) did not measure their subjects' CS functions, their subjects most likely had both VF *and* CS loss since the majority of ocular diseases result in concurrent loss of VF and CS. Even our FOV size estimate for navigation under the lowest image contrast level (32.1° diam.) differs greatly from Lovie-Kitchin et al.'s (1990) estimate. The variability in the characteristics of their small subject sample ($n = 10$) may explain why their estimated FOV size for navigation is significantly larger (74° diameter) compared to the estimates from the current study as well as other mobility studies (Haymes et al., 1996; Pelli, 1987).

4.2. Significant viewing factors for navigation performance

The results of the current study are in agreement with previous mobility research in that navigation performance became significantly impaired with reductions in FOV and contrast (Brown et al., 1986; Geruschat et al., 1998; Hassan, Lovie-Kitchin, & Woods, 2002; Haymes et al., 1996; Kuyk, Elliott, & Fuhr, 1998; Long et al., 1990; Lovie-Kitchin et al., 1990; Marron & Bailey, 1982).

For the navigation outcome measures of log latency and log walk time, the debilitating effects of a reduced FOV on navigation performance were similar across all image contrast levels. The same however was not true for the number of obstacle contacts.

For log latency and log walk time, navigation performance was significantly better under the 40° FOV than navigation performance under the 20° FOV which in turn was significantly better than the navigation performance under the 10° FOV size. For the number of obstacle contacts, navigation performance under low image contrast was significantly better under the 40° FOV than performance under either the 10° or 20° FOV. Under medium and high image contrast, navigation performance was significantly better under the 40° FOV than the navigation performance under the 10° FOV, but no significant difference in performance was found between the 20° and 40° FOV.

For the effects of image contrast on navigation, we found that performance was significantly worse under low image contrast compared to high image contrast for all navigation measures. Significant differences in performance were also found between medium and high image contrast levels but only for the navigation measure of log latency. No significant difference in navigation performance was found between medium and high image contrast for walk time and the number of obstacle contacts.

We found that neither binocularity nor image chromaticity significantly affected navigation performance under the different FOV and image contrast levels (Tables 1 and 2). This finding contrasts to Elliott, Patla, and Furniss (2000) who reported that stereoacuity was a significant predictor of the percentage of obstacle hits when stepping over a high obstacle as well as the height of toe clearance over low obstacles in a real-world obstacle course.

It is unclear as to why we did not find a significant binocularity effect for a mobility task that involved detecting and navigating around different obstacles. One possible reason may relate to the fact that subjects in the current study may have had less depth perception in the HMD compared to that experienced in the real world by Elliott et al.'s (2000) subjects because of the limited spatial resolution of the headset displays. Thus any binocularity effect present in the current study may have been reduced.

4.3. Application of findings

HMDs are currently used in many military applications to augment performance either by enhancing viewing conditions (as is the case with night vision goggles), or by aiding information retrieval in time-dependent situations (e.g. heads-up displays for fighter pilots). Despite their use, little is known about what display parameters result in optimal performance. The findings in this study can be used to aid HMD design and assist in prescribing the most cost-effective device.

Our finding of no demonstrable advantage to navigating with a HMD that has color and binocular displays suggests that these features are not required in such assistive mobility devices. The exclusion of these design features may result in minimizing device weight, size and cost while not compromising the efficiency of navigation performance.

Another factor that should be considered when prescribing HMDs to augment navigation performance includes the contrast level of the environment under which the device will be used and/or the CS level of the user. The findings of our study suggest that navigating with a HMD will be affected by reductions in image contrast. Unlike at low contrast levels, a smaller FOV HMD device may be used without jeopardizing performance if the navigation task will be performed under high contrast conditions. If the contrast level of the environment and /or user is unknown, our results suggest that the HMD should have a FOV of at least 32.1° diameter for a goal-orientated navigation task.

4.4. Possible limitations of the study

The navigation assessments investigated in the current study were measured in the controlled and reproducible environment of an immersive virtual reality system. Even though such a system enabled the unique opportunity to independently vary both image contrast and FOV in order to systematically assess their effects on navigation performance, it is unknown how navigation performance in the virtual world relates to navigation performance in the real world. The majority of earlier mobility studies have measured navigation performance either on indoor obstacle courses or real world courses that have natural fluctuations in ambient illumination and contain dynamic obstacles. Kuyk et al. (1998) showed that results obtained using a laboratory controlled obstacle course correlated well with the findings obtained using 'real world' outdoor and indoor mobility routes. Further research is required however to determine how well navigation performance in a virtual world correlates to performance in the real world.

It is also possible that issues related to balance and other locomotor factors such as uncertainty associated with walking within a virtual environment may have affected the navigation performance of our subjects. To minimize these effects, subjects were always given adequate time in the practice trials before the experiment to acquaint themselves with walking in such a virtual environment. Additionally, we found that as the FOV size decreased, subjects spent significantly more time "standing" (defined as having a walking speed $\leqslant 0.1\ \mathrm{ms}^{-1}$) during the walk time phase ($F_{(1,299)} = 87.7$, $p < .001$). This suggests that as the FOV size decreased, mobility performance decreased as a result of "navigation difficulties" rather than balance or locomotor issues because subjects needed to stop or significantly slow down in order to re-orientate themselves.

In conclusion, the results of the current study suggest that any reduction in FOV from 40° results in significant increases in latency and walk time. For the navigation task in this study, the size of the FOV required for safe navigation ranged between 10.9° and 32.1° in diameter and was dependent on average image contrast. We also found that navigation performance was not significantly affected by the presence or absence of binocularity or color displays.

Our findings suggest that HMDs designed to augment navigation performance can be dispensed without color and binocular displays and its FOV size depends in part on the expected contrast level under which the navigation task is to be performed. In circumstances where it is not clear as to what the contrast level will be, the results of our study suggest that the HMD should have a minimum FOV of approximately 32° in diameter so as not to significantly reduce travel safety.

Acknowledgments

We gratefully thank all of the subjects who participated willingly and generously in this study. We would also like to thank Beatrice Munoz, MS, for her assistance with the statistical analysis of the data. This project was supported by a US Army Research Laboratory HRED Grant #W911NF-04-1-0059.

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